Dark Matter Coupling to Electroweak Gauge and Higgs Bosons

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Based on arXiv:1305.0021 in collaboration with Edward W. Kolb and Lian-Tao Wang.

Sept. 20, 2013

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Motivation - Methodology

Two methodologies in dark matter particle theory

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Top-Down $\downarrow$
UV complete QFT model for dark matter;
its connection with Standard Model (SM) particles;
Phenomenology of the model.

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Effective operators capturing DM-SM effective coupling;
Model-independent study of phenomenology.

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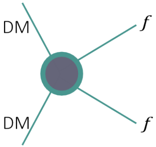
Bottom-Up ↑
Effective operators capturing DM-SM effective coupling;
Model-independent study of phenomenology.

In this presentation we adopt the bottom-up methodology.

Motivation - General

There has been much study in the effective coupling between dark matter and SM fermions, e.g. M. Beltran et. al., JHEP 1009, 037 (2010).



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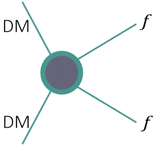

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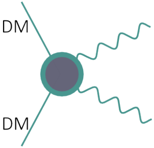

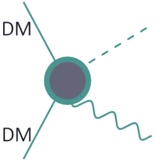

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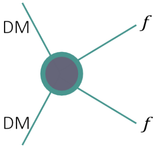

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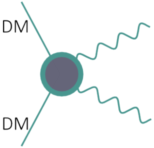

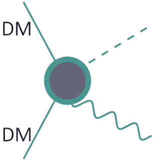

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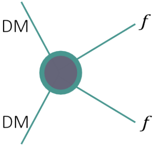

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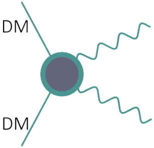

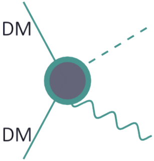

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It is worthwhile to study the
DM effective couplings to electroweak and higgs bosons.

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Fermi-LAT
possible indirect detection signals

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For example, the suspected $130\mathrm{GeV}$ photon excess as a possible signal of DM annihilation.
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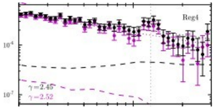

(figure from 1204.2797)

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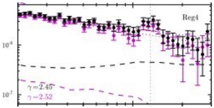

(figure from 1204.2797)

Energy spectral line $\Rightarrow$ 2 particles final state,
at least one photon.

i.e. the photon is likely a product directly from annihilation, rather than the decay product of some heavy particle.

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- Only **one** species of stable DM particle, maybe complex scalar, Dirac or Majorana fermion.
- The stable DM particle is SM gauge neutral.
- DM sector does **not** participate in electroweak symmetry breaking (EWSB).

  A similar EFT study but with DM sector involved in EWSB has been considered in R. Cotta, J. Hewett, M. Le, and T. Rizzo (2012), 1210.0525.

Assumptions on "Dominating Aspects"

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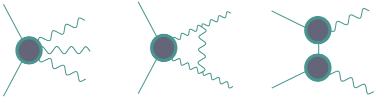

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- Λ is the cutoff scale, e.g. might be the mass scale of some heavy intermediator.

Typical Feynman Diagrams

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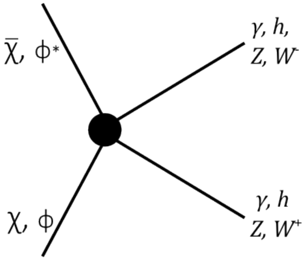
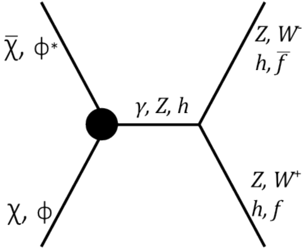


vertex diagram

- No tree-level coupling to SM fermions through vertex diagram, because J_{SM} contains SM bosonic fields only.

Typical Feynman Diagrams



s-channel diagram

- There **is** tree-level coupling to SM fermions through s-channel diagram.
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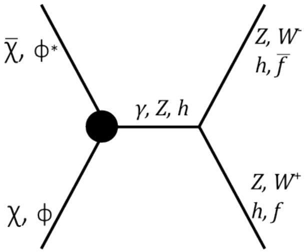

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So...

If operator leads to s-channel diagrams
$\Rightarrow$ strongly limited by direct detection (tree level).

If operator leads **only** to vertex diagrams
$\Rightarrow$ less contraint from direct detection (1-loop level).

Writing down the effective operators...

The forms of J_{DM} are relatively simple:

Scalar: $\phi^\dagger \phi$, $\left(\phi^\dagger \partial_\mu \phi + h.c.\right)$, $i\left(\phi^\dagger \partial_\mu \phi - h.c.\right)$

Dirac: $\chi^\dagger \chi$, $\chi^\dagger i\gamma^5 \chi$, $\chi^\dagger \gamma^\mu \chi$, $\chi^\dagger \gamma^{\mu 5} \chi$, $\chi^\dagger \gamma^{\mu\nu} \chi$

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Classify operators by the Lorentz properties of J_{DM}:

Scalar / pseudo-scalar coupling, e.g. $J_{SM} = B_{\mu\nu}B^{\mu\nu}$.
Vector / axial vector couling, e.g. $J_{SM} = \left(B_{\lambda\mu}Y_H\, H^\dagger D^\lambda H + h.c.\right)$.
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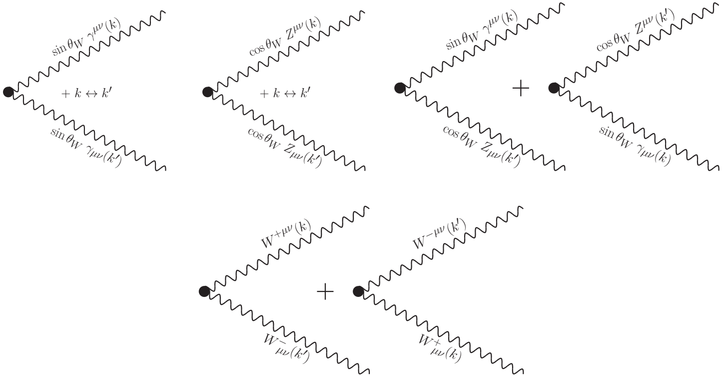
— [50 Operators in Total] —

Scalar Coupling – Example

$J_{SM} = W^a_{\mu\nu}\ W^{a\,\mu\nu}$:

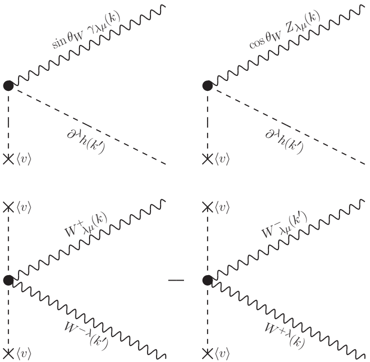


(incoming DM lines omitted)

Alternatives: $W^a_{\mu\nu}\ \widetilde{W}^{a\,\mu\nu}$, $B_{\mu\nu}\ B^{\mu\nu}$, $B_{\mu\nu}\ \widetilde{B}^{\mu\nu}$

Vector Coupling – Example

$J_{SM} = (W_{\lambda\mu}\, H^\dagger t^a D^\lambda H + h.c.)$:



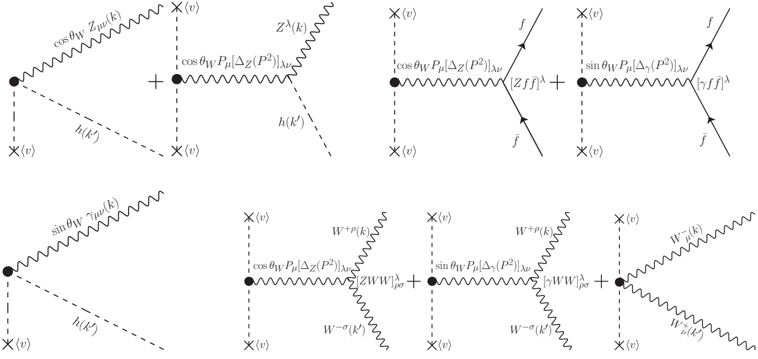
(incoming DM lines omitted)

Alternatives: $W^a t^a \longrightarrow \widetilde{W}^a t^a, \;\; B\, Y_H, \;\; \widetilde{B}\, Y_H;$

$(... + h.c.) \longrightarrow i(... - h.c.)$ (in final state $\partial^\lambda h \to Z^\lambda \langle v \rangle$)

Tensor Coupling – Example

$J_{SM} = W^a_{\ \mu\nu} H^\dagger t^a H$:



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- For each operator, for each final state, compute σv (and hence branching ratios), which depends on
  1) the cutoff scale Λ (as coupling strength), and
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- $\sigma v \Longrightarrow$ relic abundance and photon signal strength.

Select Operators

2 variables: Λ, M

3 constraints: Relic abundance (Λ, M)
Indirect signal: Line strength (Λ, M)
Line energy (M)
taken non-rel. limit $v \ll 1$

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This enables us to

1. From spectral lines and branching ratios, select operators and identify final states;
2. Determine M from line energy;
3. Fix Λ from relic abundance $\Omega_{DM} h^2 = 0.11$;
4. Pick the operators producing the desired line strengths.

Results - Example

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Assume $130\mathrm{GeV}$ gamma-ray line; $v \sim 10^{-3}$ negligiable.

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  $M = 130\mathrm{GeV}; \quad \gamma Z$ at $114\mathrm{GeV}$, γh at $100\mathrm{GeV}$.
- $130\mathrm{GeV}$ line from $\gamma Z \Rightarrow$
  $M = 144\mathrm{GeV}; \quad \gamma\gamma$ at $144\mathrm{GeV}$, γh at $117\mathrm{GeV}$.

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- $130\mathrm{GeV}$ line from $\gamma Z \Rightarrow$
  $M = 144\mathrm{GeV}$; $\gamma\gamma$ at $144\mathrm{GeV}$, γh at $117\mathrm{GeV}$.
- $130\mathrm{GeV}$ line from $\gamma h \Rightarrow$
  $M = 155\mathrm{GeV}$; $\gamma\gamma$ at $155\mathrm{GeV}$, γZ at $142\mathrm{GeV}$.

Results - Example

Table : σv in units of $10^{-27}\mathrm{cm}^3\mathrm{s}^{-1}$, given value of Λ necessary for $\Omega_{DM} h^2 = 0.11$.

Operators	If $130\mathrm{GeV}$ line from $\gamma\gamma$ final state	If $130\mathrm{GeV}$ line from γZ final state
$\Lambda^{-3}\ \bar{\chi} i\gamma^5\chi\ B_{\mu\nu}B^{\mu\nu}$ $\Lambda^{-3}\ \bar{\chi} i\gamma^5\chi\ B_{\mu\nu}\widetilde{B}^{\mu\nu}$	15	6
$\Lambda^{-3}\ \bar{\chi} i\gamma^5\chi\ W^a_{\mu\nu}W^{a\,\mu\nu}$ $\Lambda^{-3}\ \bar{\chi} i\gamma^5\chi\ W^a_{\mu\nu}\widetilde{W}^{a\,\mu\nu}$	0.7-0.8	3-4
comments	$M = 130\mathrm{GeV}$ extra line at $114\mathrm{GeV}$ due to γZ final state	$M = 144\mathrm{GeV}$ extra line at $144\mathrm{GeV}$ due to $\gamma\gamma$ final state

$[\gamma Z/\gamma\gamma]$ ratio: BB operators 0.4, WW operatros 4.5.

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Results

Assuming the $130\mathrm{GeV}$ line has the highest branching ratio,

We found **13** operators that may simultaneously satisfy $\Omega_{DM} h^2 = 0.11$ and $[\sigma v]_{\gamma \text{final state}} \sim 10^{-27} \mathrm{cm}^3 \mathrm{s}^{-1}$.

Matching with general indirect signals can be done in a similar fashion.

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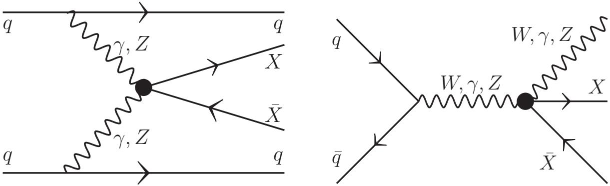
- Even without the assumption that the $130\mathrm{GeV}$ line is from DM annilation, our study provides a useful general picture about indirect detection signals.

Follow-Up Studies

- Photon continuum spectrum due to the decay of Z, W, h and heavy f in final states. [$\rightarrow$ next talk by M. A. Fedderke]

- Collider constraints.



Thank You!

Scalar / Pseudo-scalar Couplings

$$\left.\begin{array}{r}\phi^\dagger\phi\\ \bar{\chi}\chi\\ \bar{\chi}i\gamma^5\chi\end{array}\right\}\times\begin{cases}H^\dagger H & \text{with final state } hh,\ ZZ,\ W^+W^-,\ \bar{f}f\\ \\ B_{\mu\nu}\ B^{\mu\nu} & \text{with final states } \gamma\gamma,\ \gamma Z,\ ZZ\\ B_{\mu\nu}\ \widetilde{B}^{\mu\nu} & \text{with final states } \gamma\gamma,\ \gamma Z,\ ZZ\\ W^a_{\mu\nu}\ W^{a\,\mu\nu} & \text{with final states } \gamma\gamma,\ \gamma Z,\ ZZ,\ W^+W^-\\ W^a_{\mu\nu}\ \widetilde{W}^{a\,\mu\nu} & \text{with final states } \gamma\gamma,\ \gamma Z,\ ZZ,\ W^+W^-\end{cases}$$

where $B_{\mu\nu} \equiv \partial_\mu B_\nu - \partial_\nu B_\mu$, $\quad \widetilde{B}_{\mu\nu} \equiv \frac{1}{2}\epsilon_{\mu\nu\rho\sigma}B^{\rho\sigma}$.

Scalar / Pseudo-scalar Couplings

$$\left.\begin{matrix} \phi^\dagger\phi \\ \bar{\chi}\chi \\ \bar{\chi}i\gamma^5\chi \end{matrix}\right\} \times \begin{cases} H^\dagger H & \text{with final state } hh,\ ZZ,\ W^+W^-,\ \bar{f}f \\ B_{\mu\nu}\ B^{\mu\nu} & \text{with final states } \gamma\gamma,\ \gamma Z,\ ZZ \\ B_{\mu\nu}\ \widetilde{B}^{\mu\nu} & \text{with final states } \gamma\gamma,\ \gamma Z,\ ZZ \\ W^a_{\mu\nu}\ W^{a\,\mu\nu} & \text{with final states } \gamma\gamma,\ \gamma Z,\ ZZ,\ W^+W^- \\ W^a_{\mu\nu}\ \widetilde{W}^{a\,\mu\nu} & \text{with final states } \gamma\gamma,\ \gamma Z,\ ZZ,\ W^+W^- \end{cases}$$

where $B_{\mu\nu} \equiv \partial_\mu B_\nu - \partial_\nu B_\mu, \quad \widetilde{B}_{\mu\nu} \equiv \frac{1}{2}\epsilon_{\mu\nu\rho\sigma}B^{\rho\sigma}$.

- $\phi^\dagger\phi\, H^\dagger H$ is dropped because it is of dim 4.

  The “higgs protal” operators $\bar{\chi}\chi H^\dagger H$ and $\bar{\chi}i\gamma^5\chi H^\dagger H$ are of mass dimension 5.

  Vertex diagrams and higgs mediated s-channel diagrams. Tree-level coupling to SM fermions, but no to photon.

Scalar / Pseudo-scalar Couplings

$$\left.\begin{array}{r}\phi^\dagger\phi\\ \bar\chi\chi\\ \bar\chi i\gamma^5\chi\end{array}\right\}\times\begin{cases}H^\dagger H & \text{with final state } hh,\ ZZ,\ W^+W^-,\ \bar f f\\ B_{\mu\nu}\ B^{\mu\nu} & \text{with final states } \gamma\gamma,\ \gamma Z,\ ZZ\\ B_{\mu\nu}\ \widetilde{B}^{\mu\nu} & \text{with final states } \gamma\gamma,\ \gamma Z,\ ZZ\\ W^a_{\mu\nu}\ W^{a\,\mu\nu} & \text{with final states } \gamma\gamma,\ \gamma Z,\ ZZ,\ W^+W^-\\ W^a_{\mu\nu}\ \widetilde{W}^{a\,\mu\nu} & \text{with final states } \gamma\gamma,\ \gamma Z,\ ZZ,\ W^+W^-\end{cases}$$

where $B_{\mu\nu} \equiv \partial_\mu B_\nu - \partial_\nu B_\mu, \quad \widetilde{B}_{\mu\nu} \equiv \frac{1}{2}\epsilon_{\mu\nu\rho\sigma}B^{\rho\sigma}$.

- $\phi^\dagger\phi\, H^\dagger H$ is dropped because it is of dim 4.

  The "higgs protal" operators $\bar\chi\chi H^\dagger H$ and $\bar\chi i\gamma^5\chi H^\dagger H$ are of mass dimension 5.

  Vertex diagrams and higgs mediated s-channel diagrams. Tree-level coupling to SM fermions, but no to photon.

- The other operators are of dim 6 (scalar DM) or dim 7 (fermionic DM). Vertex diagrams only.

Vector / Axial-Vector Couplings

$$\left.\begin{array}{r}\left(\phi^\dagger \partial^\mu \phi + h.c.\right)\\ i\left(\phi^\dagger \partial^\mu \phi - h.c.\right)\\ \bar{\chi}\gamma^\mu\chi\\ \bar{\chi}\gamma^{\mu 5}\chi\end{array}\right\}\times\left\{\begin{array}{l}\left(B_{\lambda\mu} Y_H\, H^\dagger D^\lambda H + h.c.\right) \text{ with final states } \gamma h,\ Zh\\ \left(\widetilde{B}_{\lambda\mu} Y_H\, H^\dagger D^\lambda H + h.c.\right) \text{ with final states } \gamma h,\ Zh\\ i\left(B_{\lambda\mu} Y_H\, H^\dagger D^\lambda H - h.c.\right) \text{ with final states } \gamma Z,\ ZZ\\ i\left(\widetilde{B}_{\lambda\mu} Y_H\, H^\dagger D^\lambda H - h.c.\right) \text{ with final states } \gamma Z,\ ZZ\\ \left(W^a{}_{\lambda\mu}\, H^\dagger t^a D^\lambda H + h.c.\right) \text{ with final states } \gamma h,\ Zh,\ W^+W^-\\ \left(\widetilde{W}^a{}_{\lambda\mu}\, H^\dagger t^a D^\lambda H + h.c.\right) \text{ with final states } \gamma h,\ Zh,\ W^+W^-\\ i\left(W^a{}_{\lambda\mu}\, H^\dagger t^a D^\lambda H - h.c.\right) \text{ with final states } \gamma Z,\ ZZ,\ W^+W^-\\ i\left(\widetilde{W}^a{}_{\lambda\mu}\, H^\dagger t^a D^\lambda H - h.c.\right) \text{ with final states } \gamma Z,\ ZZ,\ W^+W^-\end{array}\right.$$

$Y_H = 1/2$ is the hypercharge of H, and t^a are the $SU(2)_L$ generators.

Vector / Axial-Vector Couplings

$$\left.\begin{array}{r}\left(\phi^\dagger\partial^\mu\phi + h.c.\right)\\ i\left(\phi^\dagger\partial^\mu\phi - h.c.\right)\\ \bar{\chi}\gamma^\mu\chi\\ \bar{\chi}\gamma^{\mu 5}\chi\end{array}\right\}\times\left\{\begin{array}{l}\left(B_{\lambda\mu}Y_H\,H^\dagger D^\lambda H + h.c.\right)\text{ with final states }\gamma h,\ Zh\\ \left(\widetilde{B}_{\lambda\mu}Y_H\,H^\dagger D^\lambda H + h.c.\right)\text{ with final states }\gamma h,\ Zh\\ i\left(B_{\lambda\mu}Y_H\,H^\dagger D^\lambda H - h.c.\right)\text{ with final states }\gamma Z,\ ZZ\\ i\left(\widetilde{B}_{\lambda\mu}Y_H\,H^\dagger D^\lambda H - h.c.\right)\text{ with final states }\gamma Z,\ ZZ\\ \left(W^a{}_{\lambda\mu}\,H^\dagger t^a D^\lambda H + h.c.\right)\text{ with final states }\gamma h,\ Zh,\ W^+W^-\\ \left(\widetilde{W}^a{}_{\lambda\mu}\,H^\dagger t^a D^\lambda H + h.c.\right)\text{ with final states }\gamma h,\ Zh,\ W^+W^-\\ i\left(W^a{}_{\lambda\mu}\,H^\dagger t^a D^\lambda H - h.c.\right)\text{ with final states }\gamma Z,\ ZZ,\ W^+W^-\\ i\left(\widetilde{W}^a{}_{\lambda\mu}\,H^\dagger t^a D^\lambda H - h.c.\right)\text{ with final states }\gamma Z,\ ZZ,\ W^+W^-\end{array}\right.$$

$Y_H = 1/2$ is the hypercharge of H, and t^a are the $SU(2)_L$ generators.

- All operators are of mass dimension 8. Vertex diagrams only.

Vector / Axial-Vector Couplings

$$\left.\begin{array}{r} \left(\phi^\dagger \partial^\mu \phi + h.c.\right) \\ i\left(\phi^\dagger \partial^\mu \phi - h.c.\right) \\ \bar{\chi}\gamma^\mu \chi \\ \bar{\chi}\gamma^{\mu 5}\chi \end{array}\right\} \times \begin{cases} \left(B_{\lambda\mu} Y_H\, H^\dagger D^\lambda H + h.c.\right) \text{ with final states } \gamma h,\ Zh \\ \left(\widetilde{B}_{\lambda\mu} Y_H\, H^\dagger D^\lambda H + h.c.\right) \text{ with final states } \gamma h,\ Zh \\ i\left(B_{\lambda\mu} Y_H\, H^\dagger D^\lambda H - h.c.\right) \text{ with final states } \gamma Z,\ ZZ \\ i\left(\widetilde{B}_{\lambda\mu} Y_H\, H^\dagger D^\lambda H - h.c.\right) \text{ with final states } \gamma Z,\ ZZ \\ \left(W^a_{\lambda\mu}\, H^\dagger t^a D^\lambda H + h.c.\right) \text{ with final states } \gamma h,\ Zh,\ W^+W^- \\ \left(\widetilde{W}^a_{\lambda\mu}\, H^\dagger t^a D^\lambda H + h.c.\right) \text{ with final states } \gamma h,\ Zh,\ W^+W^- \\ i\left(W^a_{\lambda\mu}\, H^\dagger t^a D^\lambda H - h.c.\right) \text{ with final states } \gamma Z,\ ZZ,\ W^+W^- \\ i\left(\widetilde{W}^a_{\lambda\mu}\, H^\dagger t^a D^\lambda H - h.c.\right) \text{ with final states } \gamma Z,\ ZZ,\ W^+W^- \end{cases}$$

$Y_H = 1/2$ is the hypercharge of H, and t^a are the $SU(2)_L$ generators.

- All operators are of mass dimension 8. Vertex diagrams only.
- The operators $\left(\phi^\dagger \partial^\mu \phi + h.c.\right)\left(\widetilde{B}_{\lambda\mu} Y_H\, H^\dagger D^\lambda H + h.c.\right)$ and $\left(\phi^\dagger \partial^\mu \phi + h.c.\right)\left(\widetilde{W}^a_{\lambda\mu}\, H^\dagger t^a D^\lambda H + h.c.\right)$ are total derivatives and therefore should not be included.

Tensor Couplings

$$\bar{\chi}\gamma^{\mu\nu}\chi \times \begin{cases} B_{\mu\nu} & \text{with final states } Zh,\ W^+W^-,\ f\bar{f} \\ \widetilde{B}_{\mu\nu} & \text{with final states } Zh,\ W^+W^-,\ f\bar{f} \\ & \\ B_{\mu\nu} Y_H\, H^\dagger H & \text{with final states } \gamma h,\ Zh,\ W^+W^-,\ f\bar{f} \\ \widetilde{B}_{\mu\nu} Y_H\, H^\dagger H & \text{with final states } \gamma h,\ Zh,\ W^+W^-,\ f\bar{f} \\ W^a_{\ \mu\nu} H^\dagger t^a H & \text{with final states } \gamma h,\ Zh,\ W^+W^-,\ f\bar{f} \\ \widetilde{W}^a_{\ \mu\nu} H^\dagger t^a H & \text{with final states } \gamma h,\ Zh,\ W^+W^-,\ f\bar{f} \end{cases}$$

Tensor Couplings

$$\bar{\chi}\gamma^{\mu\nu}\chi \times \begin{cases} B_{\mu\nu} & \text{with final states } Zh,\ W^+W^-,\ f\bar{f} \\ \widetilde{B}_{\mu\nu} & \text{with final states } Zh,\ W^+W^-,\ f\bar{f} \\ \\ B_{\mu\nu} Y_H\, H^\dagger H & \text{with final states } \gamma h,\ Zh,\ W^+W^-,\ f\bar{f} \\ \widetilde{B}_{\mu\nu} Y_H\, H^\dagger H & \text{with final states } \gamma h,\ Zh,\ W^+W^-,\ f\bar{f} \\ W^a_{\mu\nu} H^\dagger t^a H & \text{with final states } \gamma h,\ Zh,\ W^+W^-,\ f\bar{f} \\ \widetilde{W}^a_{\mu\nu} H^\dagger t^a H & \text{with final states } \gamma h,\ Zh,\ W^+W^-,\ f\bar{f} \end{cases}$$

- $\bar{\chi}\gamma^{\mu\nu}\chi\, B_{\mu\nu}$ and $\bar{\chi}\gamma^{\mu\nu}\chi\, \widetilde{B}_{\mu\nu}$ are of dim 5.
  Only γ and Z mediated s-channel diagrams.
  Tree-level couplings to SM fermions, but no to photons.

Tensor Couplings

$$\bar{\chi}\gamma^{\mu\nu}\chi\ \times \begin{cases} B_{\mu\nu} & \text{with final states } Zh,\ W^+W^-,\ f\bar{f} \\ \widetilde{B}_{\mu\nu} & \text{with final states } Zh,\ W^+W^-,\ f\bar{f} \\ \\ B_{\mu\nu}Y_H H^\dagger H & \text{with final states } \gamma h,\ Zh,\ W^+W^-,\ f\bar{f} \\ \widetilde{B}_{\mu\nu}Y_H H^\dagger H & \text{with final states } \gamma h,\ Zh,\ W^+W^-,\ f\bar{f} \\ W^a_{\mu\nu}H^\dagger t^a H & \text{with final states } \gamma h,\ Zh,\ W^+W^-,\ f\bar{f} \\ \widetilde{W}^a_{\mu\nu}H^\dagger t^a H & \text{with final states } \gamma h,\ Zh,\ W^+W^-,\ f\bar{f} \end{cases}$$

- $\bar{\chi}\gamma^{\mu\nu}\chi\, B_{\mu\nu}$ and $\bar{\chi}\gamma^{\mu\nu}\chi\, \widetilde{B}_{\mu\nu}$ are of dim 5.
  Only γ and Z mediated s-channel diagrams.
  Tree-level couplings to SM fermions, but no to photons.
- The other operators are of dim 7.
  Vertex diagrams, γ and Z mediated s-channel diagrams.
  Tree-level coulings to SM fermions.